Diffusion Tensor Imaging

Lecture 16

November 18, 2016

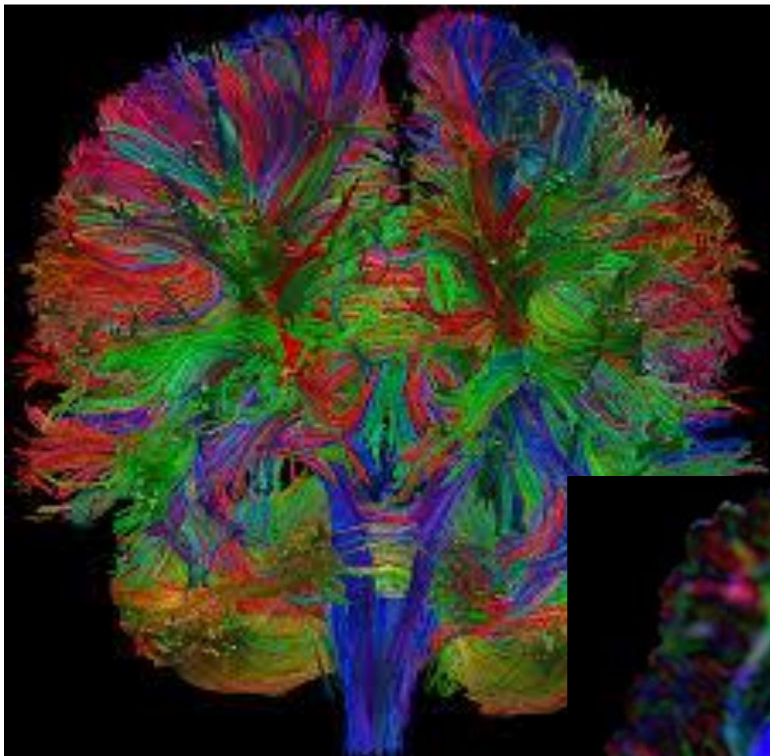
Diffusion Tensor Imaging (DTI)

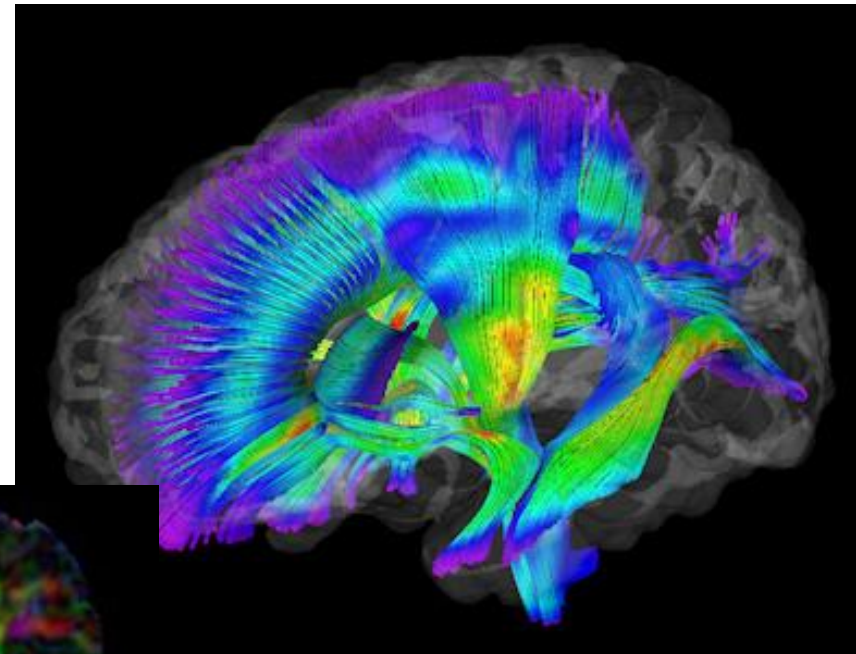
- A method to measure water diffusion using magnetic resonance
- Based on the idea that the diffusion weighted signal that we measure reflects the structure of the tissue from which it is measured
- Used to study white matter tracts both clinically and in research

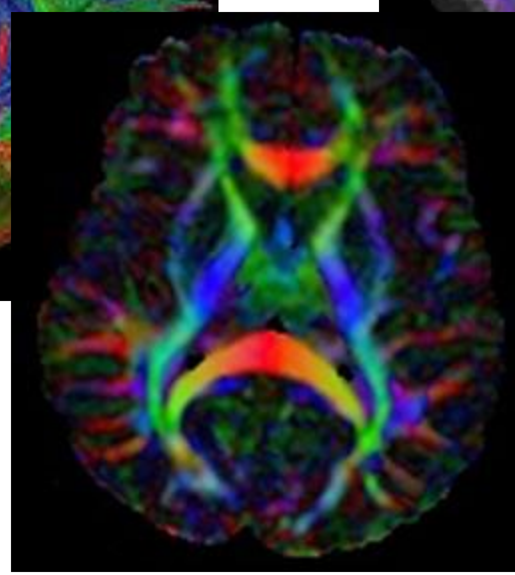
Tractography

- 3D modeling techniques used to visually represent neural tracts using data collected by diffusion tensor imaging (DTI)
- DTI was the first fiber imaging technique, limited for tractography because it is difficult to detect fiber crossings
- Also called diffusion weighted imaging
- Diffusion spectrum imaging (DSI) is method designed to overcome the limitations of DTI
- DSI measures in many different directions, but it uses a lot more magnetic gradient and acquires data in a different pattern

DTI White Matter Images







History of DTI

- 1990, Michael Moseley reported that water diffusion in white matter is anisotropic
- 1991, Douek et al. first showed that anisotropy could be exploited to map the orientation of white matter tracts
- 1992, first images submitted for patents (UK)
- 1994, Basser et al, diffusion tensor model first used for DTI

https://en.wikipedia.org/wiki/Diffusion_MRI#Diffusion_tensor_imaging
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3163395

Diffusion (in DTI)

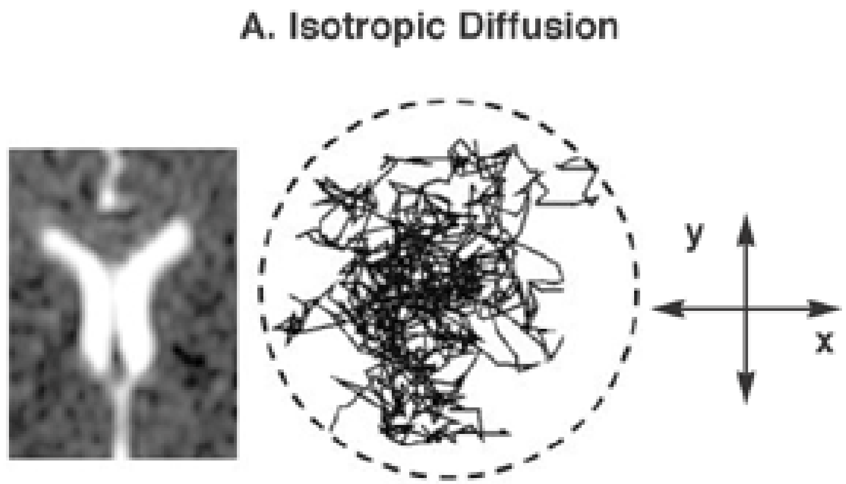
- Diffusion is extremely sensitive to differences and changes in tissue microstructure
  - Myelination/Demyelination
  - Axon damage/Loss
  - Inflammation/Edema
  - Necrosis

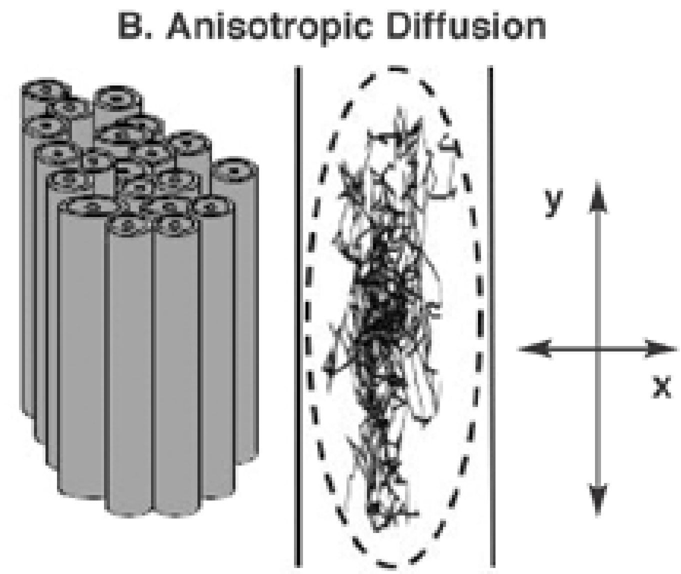
- A measure of white matter integrity?

Diffusion of Water in Tissues

- Diffusion of water molecules follows Brownian motion (random)
- With no constraints, water molecules can diffuse isotropically
- Along axons, water molecules diffuse anisotropically

Water Diffusion in Tissue





Random (stochastic) movement of particles

But in white matter, the direction is constrained leading to anisotropic diffusion

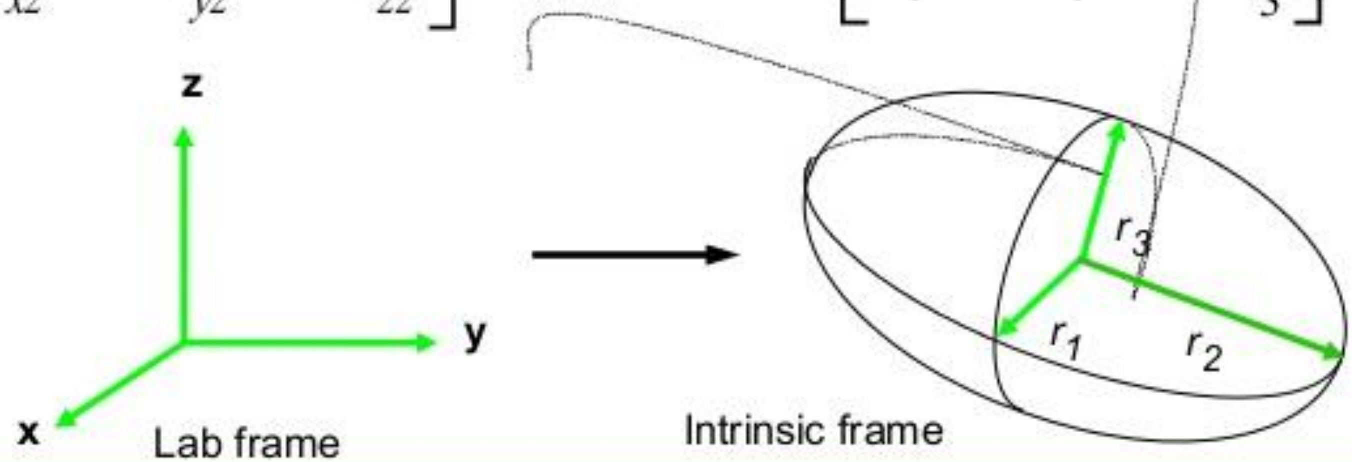
http://pubs.niaaa.nih.gov/publications/arh27-2/146-152.htm

Back to DTI

- In white matter, diffusion along the transverse axis is much slower than that along the fibers
- Diffusion weighted MR is designed to give more weight to diffusion in some directions than in others
- Acquire a collection of 7+ images with different direction encodings to compute the diffusion tensor in each voxel

The Diffusion Tensor

$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix} \xrightarrow{\text{diagonalization}} \begin{bmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{bmatrix}$$



http://www.slideshare.net/AzizPoonawalla/dti-lecture-100710

DTI Principles (continued)

Tensor Invariants

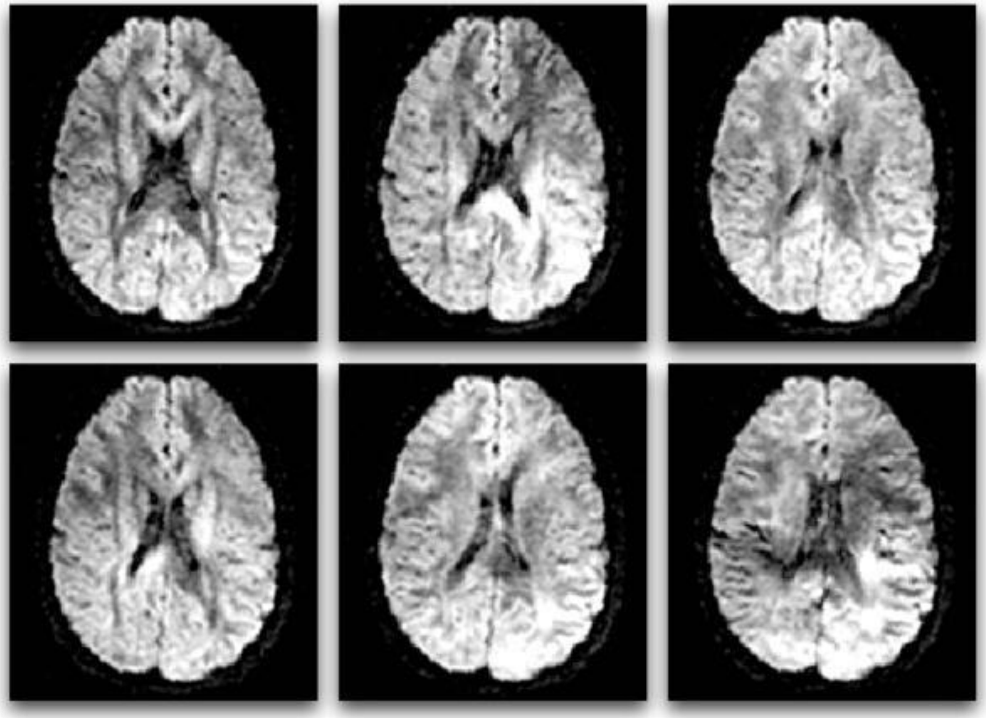
$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

- Eigenvalues: diagonalization (iterative QR factorization)
- Eigenvectors

$$\{ D_1 \quad D_2 \quad D_3 \}$$

$$\{ \vec{e}_1 \quad \vec{e}_2 \quad \vec{e}_3 \}$$

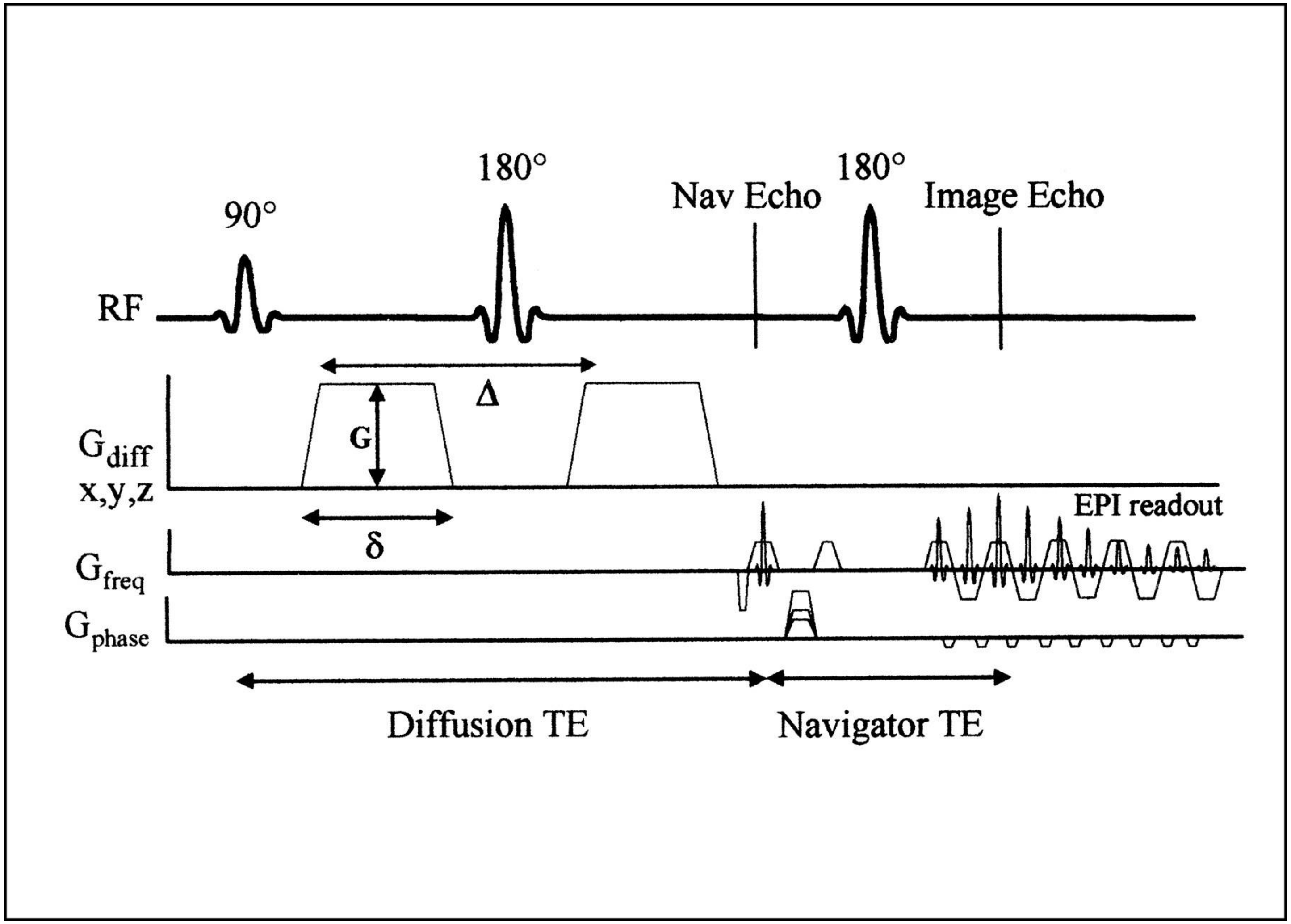
Raw Diffusion Weighted Images



White matter tracts parallel to the gradient direction appear dark in the image for that direction

Neurosurg Clin N Am. 2011 Apr; 22(2): 185–viii.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3163395/

Navigator-corrected, multi-shot, spin-echo echo-planar pulse sequence with diffusion-sensitizing gradients of amplitude (G), duration (δ), and separation (Δ).



Chad A. Holder et al. AJNR Am J Neuroradiol 2000;21:1799-1806

Compute the Eigenvalues and Eigenvectors

- Once you have the images that constitute the diffusion tensor, can find the eigenvalues and eigenvectors $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$

- Need at least 7 images (6 diffusion weighted images + one baseline image) are needed to compute the 3x3 matrix

Neurosurg Clin N Am. 2011 Apr; 22(2): 185–viii.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3163395/

Use Eigenvalues to Compute Different Measures Which Give Information about the Tissues

- Diffusion Anisotropy Measures

λ_1 = longitudinal (axial) diffusivity(AD)

$(\lambda_2 + \lambda_3)/2$ = radial diffusivity (RD)

$(\lambda_1 + \lambda_2 + \lambda_3)/3$ = mean diffusivity (MD)

$$\sqrt{\frac{1}{2}}\frac{\sqrt{(\lambda_1-\lambda_2)^2+(\lambda_1-\lambda_3)^2+(\lambda_2-\lambda_3)^2}}{\sqrt{(\lambda_1^2+\lambda_2^2+\lambda_3^2)}}$$ = fractional anisotropy (FA)

- Axial diffusivity (parallel diffusivity) is equal to the largest eigenvalue
- Radial diffusivity is perpendicular to axial diffusivity

Do These Measures Have Anatomical Significance?

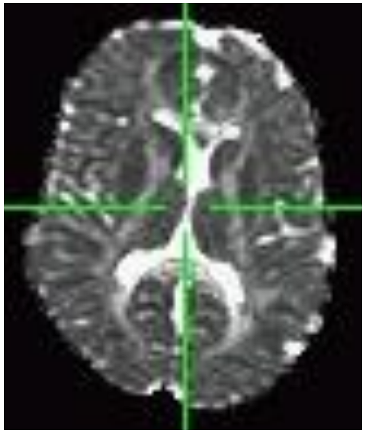
- FA = measure of microstructural integrity
- MD = inverse measure of the membrane density
- AD = variable with white matter changes and pathology
- RD = increases in white matter with demyelination

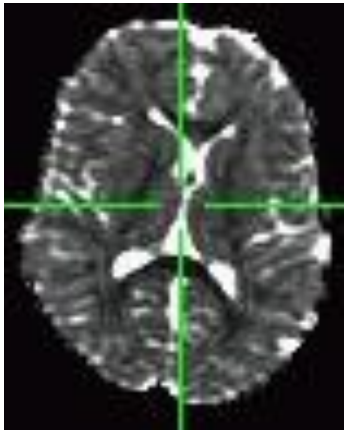
http://www.diffusion-imaging.com/2013/01/relation-between-neural-microstructure.html

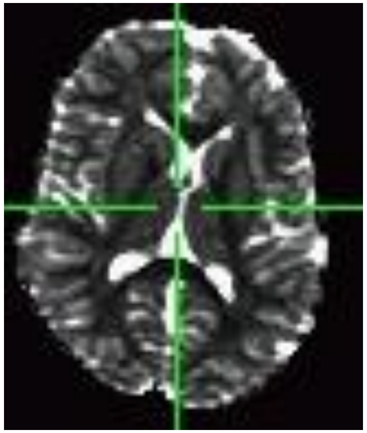
Analyzing the Data

- Several software packages exist for DTI
  - FSL: Tract based spatial statistics (TBSS)
    - Preprocessing, analysis, statistical implementation
  - DTI Studio
  - Brain Voyager
  - MrDiffusion
  - ExploreDTI
- http://www.diffusion-imaging.com/2013/03/list-of-software-tools-for-dti.html

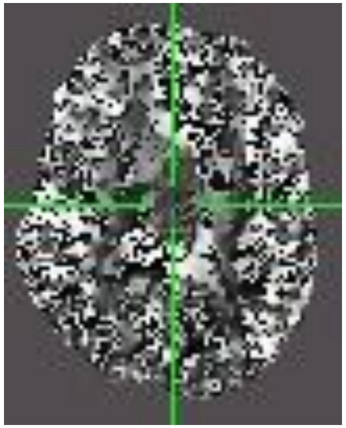
Eigenvalues and Eigenvectors

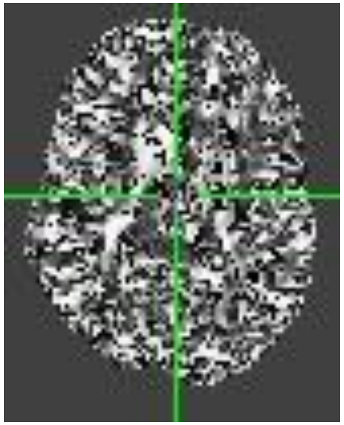


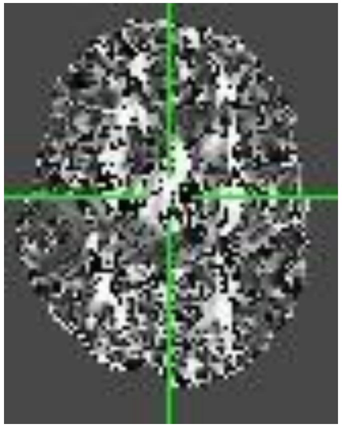




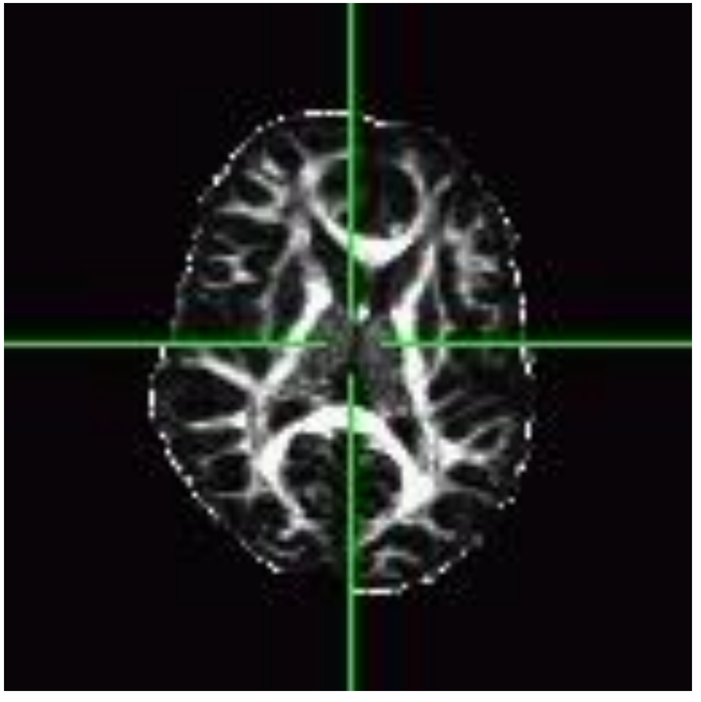
λ_1 λ_2 λ_3



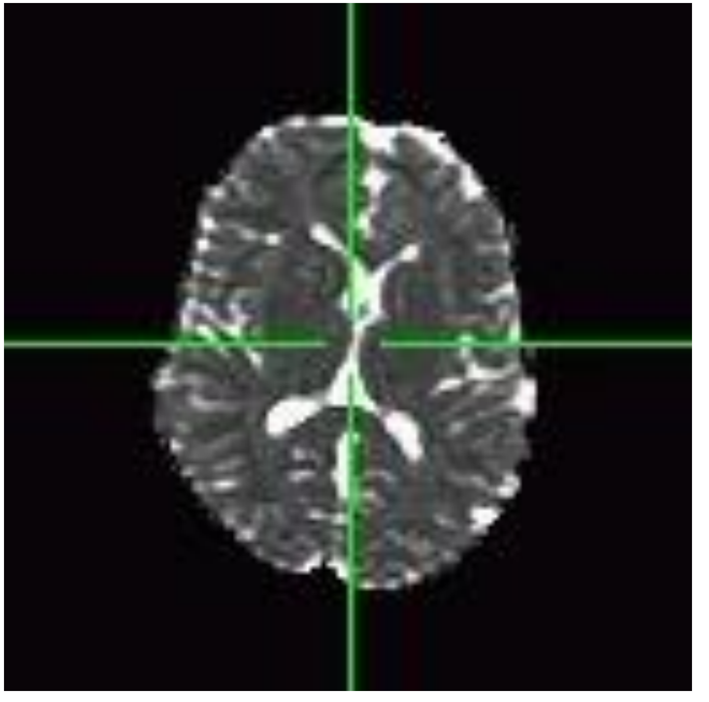




Compute FA and MD Images



FA Image



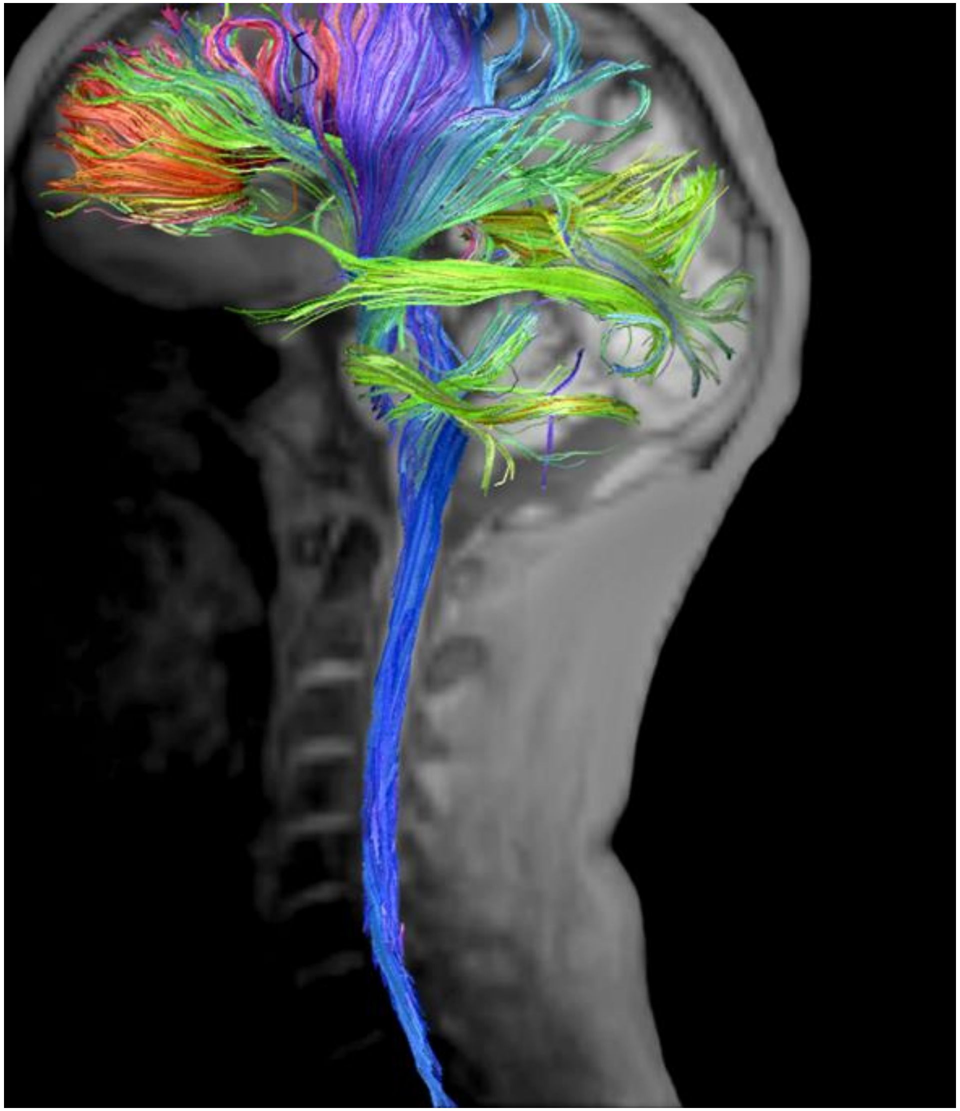
MD Image

FA and MD Image Uses

- Compute FA and MD for each subject
- Normalize these and combine groups of subjects
- Compare these measures across groups

Tractography

Apply a technique to follow and trace white matter tracks



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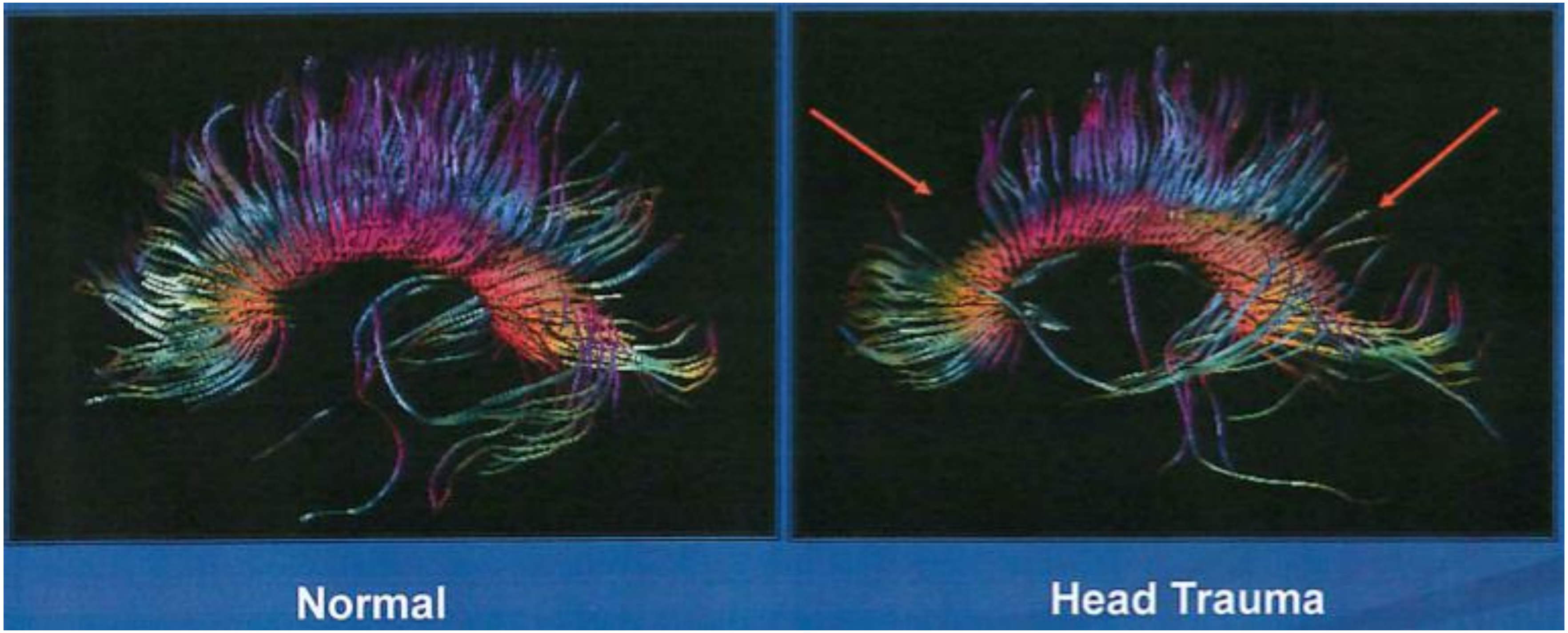
Compare White Matter Tracks in Injury



http://braininjuryhelp.com/dti-diffusion-tensor-imaging-mri/